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IMPROVED TEMPERATURE CONTROL SYSTEM OF SECONDARY VOLTAGE STANDARD BASED ON WESTON STANDARD CELLS

Roman Kochan[1], *Juergen Niemeyer*[2], *Eugen Kryloshanski*[3], *Anatoly Sachenko*[1], *Oxana Boyko*[4], *Volodymyr Kochan* [1],

[1]Institute of Computer Information Technologies, Ternopil, Ukraine.
[2] Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[3]Specialized Design Company Microelectronic and Instrumentation, Lviv, Ukraine
[4]National University "Lviv Polytechnik", Lviv, Ukraine.

Abstract – There is considered the thermistor implementation in the automatic temperature control system of secondary voltage standard of Ukraine. High sensitivity and resistance of thermistor allows decreasing the self-heating of the sensor to the negligible quantity. The significant drift of the thermistors is proposed to correct by its testing and calibration using reference RTD in the same system. The intercalibration time is proposed to increase by using thermistor's conversion characteristics prediction methodology based on artificial neural networks. There is described the general structure of proposed automatic temperature control system and evaluated its error.

Keywords: Weston Standard Cell, Temperature sensor, Error correction, Drift prediction

1. INTRODUCTION

The secondary voltage standard of Ukraine is based on three Weston Standard Cells (WSC) X489. Each of them includes four shells of WSC X482. These WSCs should provide reproducing of voltage emf with allowable deviation not more than $\Delta_{EDOP} \le \pm 0{,}6\mu V$ (±6×10-5 % / year). These requirements could be provided in the following conditions: (i) shells of WSC X482 should be isolated of environments influence; (ii) the value of emf of secondary voltage standard is average value of tens' emf of WSC X482 which are inside of secondary voltage standard and two WSCs with maximum deviation of the emf in comparison with previous are not included in output value. It is logical to use WSC instead of reference devices based on Josefson effect on this level of testing pyramid. It is connected with large price of cryogenic and high-frequency equipment for these devices. Besides the secondary voltage standard based on WSC is easy in exploitation and has less installation and ready to use time in comparison with standards based on Josefson effect [1].

The main physical quantities which influence the emf of WSC are as following: environment temperature, speed of its variation, gradient of temperature between bends of WSC. The secondary voltage standard is in the thermostable room and in addition each X489 WSC has own high quality three level thermostat (Fig.1). Shells HE1…HE4 of WSC X482 are included into each WSC X489. They are situated in the slots of aluminium thermosnap of cube shape 1. This module and foam plastic thermosnap 2 are inside contour of passive thermostat. The main task of this contour is decreasing of the influence of temperature variation and gradient of temperature field between legs of shells on the emf of WSCs. These variation and gradient are caused by imperfections of second contour of thermostating. This second contour of thermostating is active. It is made of six aluminium plates 3 which forms hollow cube. On the external side of this cube there are situated plate heaters and temperature sensors of temperature control system (two RTD – Pt 100) and layer of foam plastic isolation 4. The temperature of second contour is approximately 30 °C. The external contour of thermostating is also active. Its structure is the same as structure of second contour. The temperature of this contour is approximately 29,5°C. The three level thermostating systems of WSC X489 and precision temperature controllers allow providing such operating conditions of shells of WSC X482 (high stability of operating temperature and low gradient of temperature field) which are enough for providing metrology characteristics of secondary voltage standard.

2. REQUIREMENTS TO THE ACCURACY OF WSC'S TEMPERATURE CONTROL

It is necessary to make control of current temperature of WSCs X482 for guaranteeing the required stability of its temperature and adding correction factor. Let evaluate required accuracy of temperature control system of secondary voltage standard. The allowable deviation of the emf during one year is not more than $\Delta_{EDOP} \le \pm 0{,}6\mu V$ the allowable temperature error Δ_{TDOP} should not be more than $\Delta_{EDOP}/3$, therefore $\Delta_{TDOP} \le (\pm 0{,}6/3) = 0{,}2\mu V$. The individual temperature error of each WSC X489 should not be more than $\Delta_{TDOPI} \le 0{,}2/\sqrt{3} \approx 0{,}12\mu V$. The average temperature coefficient of emf of shell of WSC X482 is $TKE \approx 40\ \mu\text{V}/{}^{o}C$, then error of temperature measurement of each WSC X489 should not exceed $\Delta_{TDOPI} = \Delta_{TDOPI} / TKE \approx 0{,}003^{o}C$. This value of temperature measurement error could be provided if the sensitivity of temperature measurement is $\Delta_{TSENI} \approx 0{,}001^{o}C$.

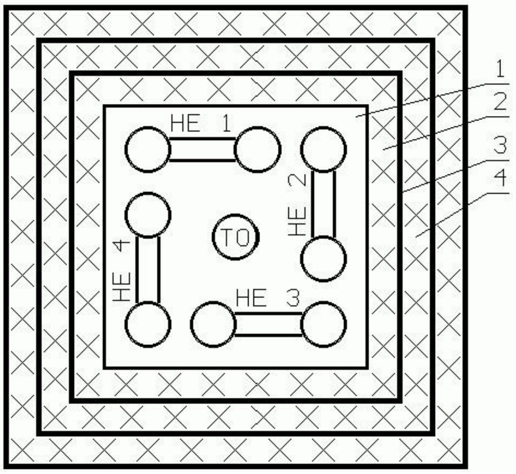

Fig.1 Structure of the thermostated WSC X489.

When we use platinum RTD Pt100 as tempera sensor (temperature coefficient of resistance $TKR_{TO} \approx 0{,}4\,\Omega/{}^{o}C$) and digital to analog converter with sensitivity $\Delta_{ADCSEN} = 1\,\mu\text{V}$, it is necessary to provide working current I through the sensor for providing sensitivity $\Delta_{TSENI} \approx 0{,}001^{o}C$.

$$I = \Delta_{ADCSEN} / (TKR_{TO} \times \Delta_{TSENI}) = 2{,}5mA \quad (1)$$

In this case the power which is detected on this RTD Pt 100 is $P = I^2 R \approx 0{,}7mW$. According to [2] the self heating of RTD Pt 100 on the temperature $\Delta_{TSN} = 0{,}2^{o}C$ demands power $P_{SN} = 10mW$. The power $0{,}7mW$ will bring self heating on the temperature $\Delta_{TS} = \Delta_{TSN} \times P / P_{SN} \approx 0{,}014^{o}C$. This error is systematic for temperature control system and could be easy corrected but its self heating makes gradient of temperature field in the zone of shells of WSC X482.

Variation of the gradient of temperature field is ten times more influential than temperature variation [3]. Therefore the allowable gradient of temperature field should not exceed $\Delta_{TGRAD} \approx 0{,}0003^{o}C$. It means that effectiveness of the temperature smoothing by internal passive thermostat should be more than $K = \Delta_{TS} / \Delta_{TGRAD} = 0{,}014^{o}C / 0{,}0003^{o}C \approx 47$. It is impossible to confirm such value of effectiveness of thermostat during exploitation of secondary voltage standard. Simulation modeling, in this case, does not have good reliability because of complex form and geterogeneous structure of the thermoshunt.

3. APPROACH TO SELF HEATING DECREASING

As it was indicated above the self heating of the sensors set ups the problem of current temperature of secondary voltage standard measurement.

Existed methods of self heating decreasing are based on using special RTD Pt500 or increasing sensitivity of measurement channel. But existed layer RTD Pt500 has low stability. Providing better than $1\,\mu\text{V}$ sensitivity makes significant difficulties during commutation and analogue to digital conversion. Existed precision digital thermometers, which could provide required error and sensitivity, has 1mA working current of RTD and more, NetDAQ of Fluke [4], RP-7000 of Franco Corradi [5], and other for example. Precision thermometers with less than 1 mA working current of RTD, F300 of AΣЛ [6], T.T.I.2 of Isotech [7] for example, has only two channels. Increasing of channel number demands using external multiplexers with stray emf not more than $0{,}1\,\mu\text{V}$. Besides indicated thermometers has large price and they demand additional equipment for automation of temperature control process.

It is proposed to use thermistor as temperature sensor for WSC X489. The high resistance and sensitivity of the thermistors allows decreasing the self heating of such sensor. The proposed approach is applied into digital thermometers type 4350 and 4351 of National Instruments [8]. But error of these thermometers is $0{,}03^{o}C$. This error is 10 times more than allowable error. Large error of indicated thermometers is defined by large drift of thermistor’s conversion characteristic. Therefore it is proposed to correct of thermistor’s drift by results of its periodic testing using RTD Pt100. In this case current will flow through RTD only during calibration of thermistor. Testing process will be done when secondary standard is not planed to be used for several days (on week-end for example). Using results of testing it is proposed to predict thermistor’s drift for next intertesting interval. It is logical to use methodology based on artificial neural networks developed by project INTAS-OPEN-97-0606 [9…11].

Let evaluate the error of thermistor’s self heating. The optimal, from the sensitivity point of view, mode of the thermistor could be computed according [12]. The comparison of the proposed solution with the RTD Pt100 will be done for the same conditions – ADC with voltage sensitivity $\Delta_{ADCSEN} = 1\,\mu\text{V}$ the required temperature sensitivity $\Delta_{TSENI} \approx 0{,}001^{o}C$. The working current of the thermistor could be computed according to the (1). The working current of the thermistor with nominal resistance $R_{TMS} \approx 10k\Omega$ (in the temperature $30^{o}C$) and temperature resistance coefficient $TKR_{TMS} \approx 4\,\%/{}^{o}C$ should be

$$I_{TMS} = \frac{\Delta_{ADCSEN} \times 100\%}{TKR_{TMS} \times R_{TMS} \times \Delta_{TSENI}} = 2{,}5\mu A \qquad (2)$$

In this case the power of the thermistor is $P_{TMS} = I_{TMS}^2 R_{TMS} \approx 0{,}6\mu W$. Experimental researches shows that self heating of the thermistor is significantly more than self heating of RTD. The power $P_{TMSSN} \approx 1{,}5mW$ bring self heating temperature $\Delta_{TMSN} = 0{,}2^oC$ for the KMT-1 type thermistors. In this case the temperature of self heating of thermistor is $\Delta_{TMSS} = \Delta_{TMSN} \times P_{TMS} / P_{TMSSN} \approx 0{,}00008^oC$. As it could be seen from presented computation the self heating temperature and gradient of the temperature field is the negligible quantity.

4. DEVELOPMENT OF THE TEMPERATURE CONTROL SYSTEM

There was developed special temperature control system for application of proposed approach. The structure of this system is presented on fig. 2. It consists of: precision RTDs Pt 100 – TO1…TO3; thermistors KMT-1 - TMS1…TMS3; reference resistors RN1, RN2; current setting resistors R1, R2; measurement module. Measurement module consists of: 8-channel multiplexer based on hermetically sealed relay RGK-15; analog to digital converter based on AD7714 chip - ΣΔ ADC of Analog Devices; controller – AT89C52 of Atmel; reference voltage source AD780 of Analog Devices. The results of measurement are indicated on LCD –TM161AAC, LEDs and beeper. Also these results could be transmitted to PC via RS232C.

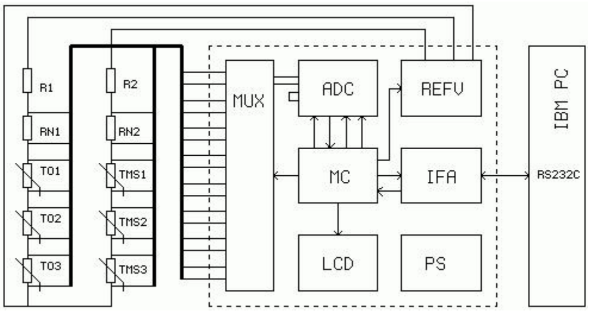

Fig. 2 Structure of temperature control system of secondary voltage standard.

MC controls the process of resistance measurement of RN2 and thermistors TMS1…TMS3 by switching appropriate channels and ADC starting. The real resistance of thermistors R_{TMS} could be found as:

$$R_{TMS} = \frac{RN2 \times (N_{TMS} - N_0)}{N_{RN2} - N_0} \qquad (3)$$

where N_{TMS}, N_{RN2}, N_0 - results of voltage measurement on: thermistor, reference resistor RN2 and shorted channel (null setting channel); RN2 – real value of the resistance of reference resistor RN2.

For increasing of the reliability of the measurement results values N_{TMS}, N_{RN2}, N_0 are compared with these values obtained during previous cycle of measurement. The result of individual neural network computing of drift correction factor should be added to R_{TMS} computed according (3). The time interval from the last calibration of each thermistor is transmitted on the input of neural network. The training process of neural network demand significant computing power therefore it is done by PC. The neural networks have good prediction properties and it is necessary to make training rather seldom (once per month). Training process demands training set which consists of values of drift of thermistor, obtained during its calibration using RTDs. The request for calibration is formed by MC by indicating message on LCD after finishing predicted intercalibration interval. The intercalibration interval is computed automatically by analysis of results of previous calibrations [13]. If the error of previous prediction is less than 80% of the allowable error of drift then intercalibration interval is increased on 20%. In opposite case the intercalibration interval is decreased on 20%. After sending request on calibration MC continues its usual work till the operator allows calibrating. After that MC makes calibration by switching on current of RTDs TO1…TO3 then ADC measure voltages of reference resistor RN1 and RTDs TO1…TO3. The real values of resistance of RTDs could be computed by (3). After calibration finishing MC sends on LCD message of temporary prohibition of secondary voltage standard exploitation. Time of this prohibition is two days. Besides MC sends request to the PC for training neural networks with simulation models of thermistors drift. There is used combination of the set of neural networks with different properties and special method of training set forming [11, 14] for decreasing number of calibration results for training prediction neural network.

5. ERROR EVALUATION

Let evaluate the error of temperature control using the proposed system. This error corresponds to the error of temperature measurement by thermistor Δ_{TTMS}. This error is defined by error of temperature measurement unit (°C) transmitting from RTD to thermistor. Therefore it is necessary to evaluate the error of temperature measurement by RTD - Δ_{TTO}. It can be evaluated as a sum of RTD error - Δ_{TO} and error of RTD's resistance measurement - Δ_{RTO}. There is no correlation between components of error therefore general error (there and below) could be computed as for independent values.

$$\Delta_{TTO} = \sqrt{\Delta_{TO}^2 + \Delta_{RTO}^2} \qquad (4)$$

The error of RTD is $\Delta_{TO} = 0{,}002°C$. Resistance of RTD is defined by replacement method according (3). Therefore resistance measurement error Δ_{RTO} could be evaluated as:

$$\Delta_{RTO} = \sqrt{\Delta^2_{RN1} + \Delta^2_{MZ} + (2\times\Delta^2_{V})} \qquad (5)$$

where Δ_{RN1} - error of reference resistor; Δ_{MZ} - error of replacement method; Δ_{V} - error of discretization.

In the same time reference resistance error Δ_{RN1} could be evaluated using its relative error - $\delta_{RN1} = 0{,}0005\%$ and sensitivity of RTD $TKR_{TO} \approx 0{,}4\,\Omega/^{o}C$ than $\Delta_{RN1} = \dfrac{\delta_{RN1}\times RN1}{100\%\times TKR_{TO}} = 0{,}0013°C$. The replacement method error could be evaluated by equation:

$$\Delta_{MZ} = \frac{2\times\delta_{MD}\times(R_{TO}-RN1)}{(RN1\times TKR_{TO})} = 0{,}0008°C \qquad (6)$$

where $\delta_{MD} = 0{,}003\%$ - relative error of measurement device (in this case it is two nonlinearity error of ADC AD7714 [15]); $R_{TO} \approx 112\Omega$ - resistance of the RTD in the thermostating temperature; $RN1 = 100\Omega$ - resistance of reference resistor RN1.

Discretization error Δ_{V} could be evaluated using $TKR_{TO} \approx 0{,}4\,\Omega/^{o}C$ and relative discretization error of 24-bit ADC AD7714 - $\delta_{V} = 0{,}0001\%$ for 20 significant bits. Therefore $\Delta_{V} = \delta_{V}\times R_{TO}/(100\%\times TKR_{TO}) \approx 0{,}00025°C$.

Substituting Δ_{RN1}, Δ_{MZ} and Δ_{V} into (5) we will have error of temperature measurement $\Delta_{RTO} \approx 0{,}0016°C$. Than according to (4) we can evaluate error of temperature measurement by RTD $\Delta_{TTO} \approx 0{,}0025°C$.

After calibration of the thermistor its own error Δ_{TMS} will be differ from Δ_{TTO} only on methodology error Δ_{TMSM} of the nonequivalence of the temperatures of RTD and thermistor during calibration. $\Delta_{TMS} = \sqrt{\Delta^2_{TTO} + \Delta^2_{TMSM}}$. The calibration of the thermistor is done inside of the three level thermostat and the thermistor has good thermal contact with RTD then the methodology error is not more than $\Delta_{TMSM} \le 0{,}0005°C$. Therefore $\Delta_{TMS} \approx 0{,}0026°C$. However temperature measurement using thermistor demands additional measurement of resistance of the thermistor and error of this measurement is Δ_{RTMS}. Resistance of the thermistor is calculated by (3) therefore error of its resistance measurement - Δ_{RTMS} could be evaluated according to (5)

$$\Delta_{RTMS} = \sqrt{\Delta^2_{RN2} + \Delta^2_{MZTMS} + (2\times\Delta^2_{VTMS})} \qquad (7)$$

where Δ_{RN2} - error of reference resistor RN2, which is used for measurement of the resistance of thermistor; Δ_{MZTMS} - error of the replacement method of thermistor's resistance measurement; Δ_{VTMS} - discretization error of thermistor's resistance measurement.

The error of reference resistor Δ_{RN2} could be evaluated according its relative error $\delta_{RN1} = 0{,}002\%$ and sensitivity of the thermistor $TKR_{TMS} \approx 4\,\%/^{o}C$ - $\Delta_{RN2} = \delta_{RN2}/TKR_{TMS} = 0{,}0005°C$. Discretization error Δ_{VTMS} could be evaluated by the same way as for RTD. Thermistors have large sensitivity and the discretization error is negligible small value. Replacement method error could be evaluated according (6)

$$\Delta_{MZTMS} = \frac{2\times\delta_{MD}\times(R_{TMS}-RN2)}{RN2\times TKR_{TMS}} = 0{,}0004°C$$

where $R_{TMS} \approx 12...14k\Omega$ - resistance of the thermistor's in the thermostating point; $RN2 = 10k\Omega$ - resistance of the reference resistor RN2.

Substituting of the Δ_{RN2}, Δ_{MZTMS} and Δ_{VTMS} into (7) we will have error of temperature measurement $\Delta_{TTMS} = \sqrt{\Delta^2_{TMS} + \Delta^2_{RTMS}} \approx 0{,}0028°C$. General error of temperature measurement Δ_{TSYS} should include error of drift prediction for the intercalibration interval $\Delta_{DRTMS} \approx 0{,}001°C$. In this case $\Delta_{TSYS} = \sqrt{\Delta^2_{TTMS} + \Delta^2_{DRTMS}} \approx 0{,}003°C$. This value is not more than allowable value.

CONCLUSION

Developed system provides a control of the current temperature for secondary voltage standard with required precision.

Besides the control of temperature the developed system provides an indication of the following values:

- Nominal values of emf for all WSCs of the etalon and instability of these emf during last intercalibration interval;
- Date of last calibration for secondary voltage standard and time to next calibration;
- Value of current temperature of WSC X489 and its maximal instability during last week;
- Real value of emf for all WSCs accounting temperature correction ;
- Date of last calibration of thermistors and time to next calibration of thermistors;

- Time to beginning of work after calibration of thermistors.

The developed system also provide light and sound indication of emergency mode and transmitting of indicated information to the PC via RS232C.

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Author(s):
Roman Kochan: Ph.D Student of Specialized Computer System Department, Institute of Computer Information Technologies. 3 Peremoga Square, Ternopil, 46004, Ukraine. Phone +380352-436038. Fax: +380352-436354. E-mail: rk@tanet.edu.te.ua.
Juergen Niemeyer: Director and Professor of Quantum Electronics Department, Physikalisch-Technische Bundesanstalt. 100 Bundesallee, Braunschweig, 38116, Germany. Phone: +49-531-592 2400. Fax: +49-531-592 2405. E-mail: Juergen.Niemeyer@ptb.de.
Eugen Kryloshanski: Director of Specialized Design Company Microelectronic and Instrumentation. 35 Nischynski str., Lviv, 79014, Ukraine. Phone: +380322-780-446.
Anatoly Sachenko: Professor and Director Institute of Computer Information Technologies. 3 Peremoga Square, Ternopil, 46004, Ukraine. Phone: +380352-435832. Fax: +380352-436354 . E-mail: as@tanet.edu.te.ua.
Oxana Boyko: Ph.D Student of Department of metrology, standardization and certifications, Lviv Polytechnik National University. 12 Bandery str., Lviv, 79013, Ukraine. Phone: +380352-768336. E-mail: olenka@poseidon.lviv.ua.
Volodymyr Kochan: Assistant Professor of Information Computing Systems and Control Department, Institute of Computer Information Technologies. 3 Peremoga Square, Ternopil, 46004, Ukraine. Phone +380352-436038. Fax: +380352-436354. E-mail: vk@tanet.edu.te.ua.